ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO012

ONCE RECIRCULATING ENERGY RECOVERY LINAC OPERATION OF S-DALINAC*

M. Arnold†, J. Birkhan, J. Pforr, N. Pietralla, F. Schließmann, M. Steinhorst
Technische Universität Darmstadt, Darmstadt, Germany
F. Hug, Johannes Gutenberg-Universität Mainz, Mainz, Germany

Abstract

The S-DALINAC is a thrice recirculating superconducting electron accelerator which can be either used in conventional accelerating operation or, since a major upgrade in 2015/2016 was installed, as an energy recovery linac (ERL) alternatively. A once or twice recirculating ERL operation is possible due to the layout of the accelerator. For both setups beam dynamics calculations have been performed or are under investigation at the moment. The once recirculating ERL mode was proven successfully in August 2017, which set the first German ERL into operation. The results will be discussed more in detail in this contribution.

INTRODUCTION

The superconducting linear electron accelerator S-DALINAC is in full operation since 1991 [1]. In the years 2015/2016 a major upgrade modified it to a thrice recirculating machine [2, 3]. Featuring the new recirculation beam line, a path length adjustment system was installed which enables a total phase shift of 360°. Thus the change between normal operation and an operation as an ERL is possible [4].

S-DALINAC

Figure 1 shows the floorplan of the thrice recirculating S-DALINAC. It houses two electron sources: A thermionic gun with a pre-acceleration of 250 keV and a spin-polarized source with a pre-acceleration of up to 125 keV. In the normal conducting chopper-prebuncher-section the beam is prepared for an acceleration with 3 GHz in the superconducting RF system. The injector accelerator is able to provide an energy gain of up to 10 MeV (7.6 MeV in case of recirculating operation) with currents of up to 60 µA. For recirculating operation the beam is bent into the main accelerator which then will provide an energy gain of up to 30.4 MeV. The beam can be recirculated up to three times, resulting in four passages through the main accelerator. A total energy of up to 130 MeV with currents of up to 20 µA can be reached.

Energy Recovery Linac Mode

The layout of the S-DALINAC allows a once recirculating or a twice recirculating ERL mode. In case of the once recirculating ERL operation, see Fig. 2, the beam is accelerated in the main linac and then directly bent into the second recirculation beam line. Therefore the ratio of injection energy and main linac energy gain needs to be set to 1:8. A 180° phase shift is done while travelling through the beam line. The beam is re-injected into the main accelerator at a decelerating phase so that it can be dumped at injection energy after leaving the main linac.

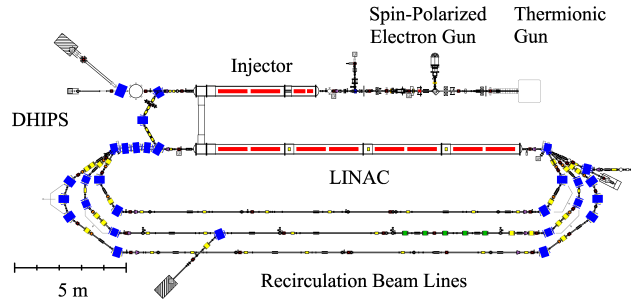

Figure 1: Floorplan of the S-DALINAC.

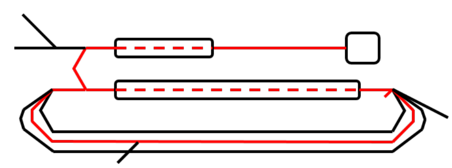

Figure 2: Scheme of the once recirculating ERL operation.

Figure 3 shows the path of the beam in case of the twice recirculating ERL mode. In contrast to the once recirculating mode the beam is first bent into the first recirculation beam line. After a second acceleration in the main linac, a 180° phase shift is performed in the second recirculation beam line. The beam is then guided through the first recirculation beam line a second time. Being twice decelerated in the end, the beam is dumped at injection energy after the last transition through the main linac. In this operation mode the ratio of injection and main linac energy gain is set to 1:4.

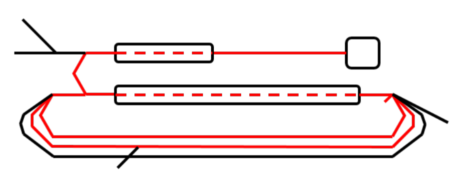

Figure 3: Scheme of the twice recirculating ERL operation.

BEAM DYNAMICS SIMULATION

To ensure the transportation of the beam, it is necessary to conduct dedicated beam dynamics simulations. During the design and installation of the thrice recirculating layout, the lattice was not optimized for ERL mode. Meanwhile

* Work supported by DFG through GRK 2128
† marnold@ikp.tu-darmstadt.de

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO012

the once and twice recirculating ERL operation have been simulated and are still under further investigations. The results of the once recirculating ERL mode are presented (done with *elegant* [5]). Figure 4 shows the beam envelope along the beam path beginning with the acceleration in the main accelerator and ending with the decelerated beam at the position of the beam dump. Figure 5 displays the dispersion curves along the same section. Both plots demonstrate a working setting: the beam envelope stays small and the dispersion curves vanish behind each arc section.

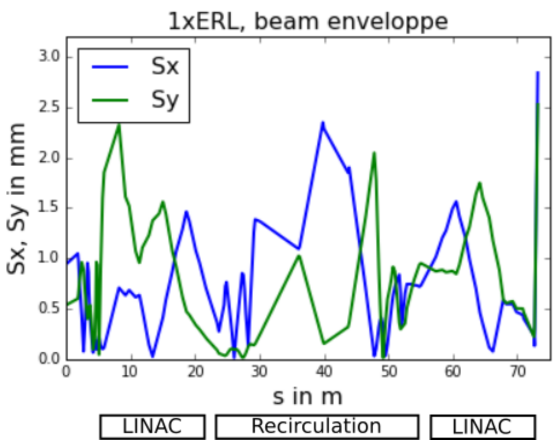

Figure 4: Simulation of horizontal (Sx) and vertical (Sy) beam envelopes for once recirculating ERL mode in x and y along the beam line.

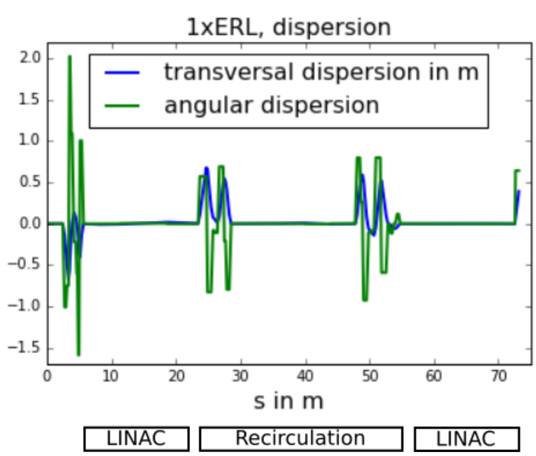

Figure 5: Simulation of dispersion curves for once recirculating ERL mode along the beam line.

ERL OPERATION

In August 2017 the first successful ERL operation took place at the S-DALINAC [6]. The main parameters of this beam setting are summarized in Table 1.

During the run four different beam settings have been investigated and compared:

- No beam in the main accelerator
- Single pass: one beam is accelerated in the main accelerator
- Once recirculating mode: two beams are accelerated in the main accelerator
- ERL mode: one beam is accelerated and decelerated in the main accelerator

Table 1: Overview of parameter settings for the once recirculating ERL operation. The current value refers to a measurement in front of the injector linac.

Parameter	Value
Energy gain injector	2.5 MeV
Energy gain linac	20.0 MeV
Current (before injector)	1.2 µA

The RF power in the first cavity of the main accelerator (A1SC01) as well as the beam currents corresponding to ERL mode (ERL cup) and once recirculating operation (E0F1 cup) have beam measured. Figure 6 gives an overview on the position of these elements and the beam path (marked in red).

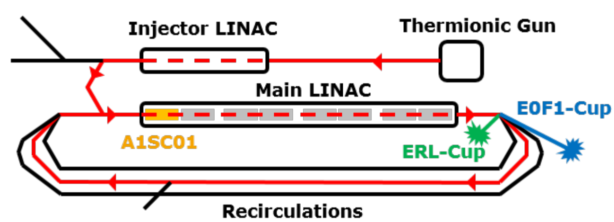

Figure 6: Beam path (red) of the once recirculating ERL mode is shown. The power of the first main linac cavity (A1SC01) as well as the beam currents corresponding to ERL (ERL cup) and once recirculating operation (E0F1) have been measured.

The results are summarized in Fig. 7. The ERL operation was done with a beam current of roughly 1 µA. The phase with no beam in the main linac (red area) defines the steady state of the cavity operation. The change of powers in A1SC01 have been measured in the other operation modes as well. For one accelerated beam a certain amount of RF power is needed for acceleration. If a second beam is accelerated, the power consumption is mainly doubled. During ERL mode the change in powers is very small, they nearly cancel out. The recovery of RF power can be seen clearly. Table 2 gives an overview on the power values measured. The energy recovered in A1SC01 during this ERL operation yields to $88.7^{+9.3}_{-5.1}$ (0.16 and 0.84 quantiles).

RF Stability Measurement

At the time the digital low level RF (LLRF) control system was installed in 2010 [7], the S-DALINAC was not able to be operated as an ERL. Thus, the system was not optimized

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO012

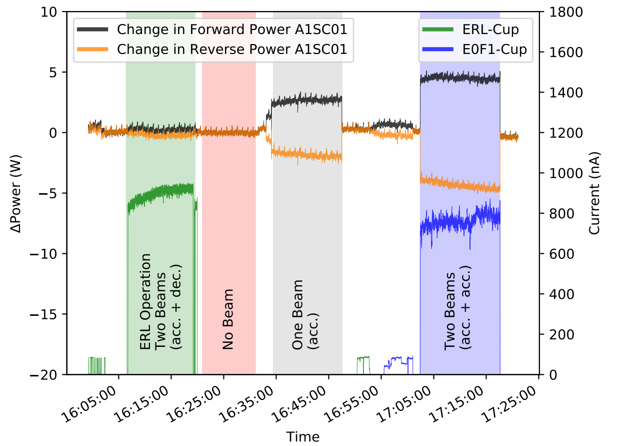

Figure 7: The forward (black curve) and reverse power (orange curve) changes of A1SC01 as well as beam currents for ERL (green curve) and once recirculating operation (blue curve) have been measured during four different beam modes: ERL mode (green area), no beam in the main linac (red area), one accelerated beam (grey area) and two accelerated beams (blue are) in the main linac.

Table 2: Mean values of the beam power with uncertainties (0.16 and 0.84 quantiles) of the distribution at the four S-DALINAC operation modes.

Operation	**Mean Beam Power (W)**
No Beam	$0.00^{+0.20}_{-0.20}$
ERL (acc. + dec.)	$0.35^{+0.49}_{-0.23}$
One Beam (acc.)	$4.42^{+1.98}_{-0.42}$
Two Beams (acc. + acc.)	$8.62^{+2.26}_{-0.94}$

for this mode. Measurements on the stability are necessary to investigate the capability of the LLRF system during ERL operation. For this reason the phase errors as well as the relative amplitude errors of all main linac cavities have been measured and compared during this four different beam modes. Figure 8 shows the results for A1SC01. The errors measured have been transformed to frequency domain. The Fourier spectra have been integrated to easily compare final values and frequencies where a relevant disturbance occur. The plot for the phase errors shows nearly the same behaviour for all four beam modes. In the measurement of the relative amplitude errors small deviations between the four different modes can be recognized. During the upcoming ERL beam times further investigations will be conducted.

CONCLUSION AND OUTLOOK

The S-DALINAC was operated successfully as first ERL in Germany in August 2017. The layout of the accelerator enables in principle a once and a twice recirculating ERL mode. For both settings beam dynamics simulations have been conducted or are under investigation at the moment.

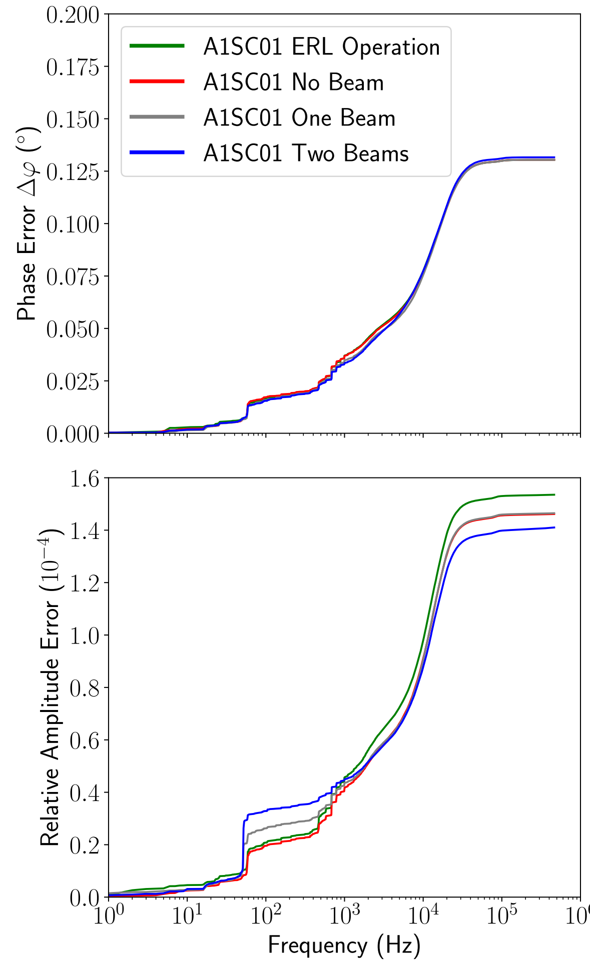

Figure 8: Phase and relative amplitude errors of A1SC01 have been measured during the four different beam modes. The data was transformed to frequency domain and integrated.

During the beam time four different machine settings have been investigated and compared to learn on the different aspects of the ERL operation such as the stability of the RF system or the efficiency of the recovery process.

In the future the twice recirculating ERL mode will be set into operation. To further improve the diagnostics of an ERL mode a system to measure all RF powers simultaneously was installed recently [8]. Further projects will deal with the topic of diagnostics dedicated for ERL usage which means multiple beams of the same energy in the same beam line.

REFERENCES

[1] N. Pietralla, "The Institute of Nuclear Physics at the TU Darmstadt", in *Nuclear Physics News*, vol. 28, no. 2, p. 4-11, 2018.

[2] M. Arnold et al., "Design, Installation and Commissioning of a Third Recirculation Beam Line Featuring an Energy Recovery Linac Mode for the S-DALINAC", in preparation.

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO012

[3] M. Arnold et al., "Construction and Status of the Thrice Recirculating S-DALINAC", in *Proc. IPAC 2017*, Copenhagen, Denmark, May 2017, paper TUPAB030 pp. 1384-1387.

[4] M. Arnold et al., "ERL Mode of S-DALINAC: Design and Status", presented at *ERL 2017*, CERN, Geneva, Switzerland, June 2017, paper MOIDCC006, pp. 40-44.

[5] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, September 2000.

[6] M. Arnold et al., "First Energy Recovery Linac Operation of S-DALINAC", in preparation.

[7] M. Konrad et al., “Digital base-band rf control system for the superconducting Darmstadt electron linear accelerator”, Phys. Rev. ST Accel. Beams, vol. 15, p. 052802, 2012.

[8] M. Steinhorst et al., “First Energy Recovery Operation at the S-DALINAC: RF Control Stability Measurements”, presented at *LINAC 2018*, Beijing, China, September 2018, paper THPO011, this conference.